Perspectives in Science (2016) 7, 323–328

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/pisc

Analysis of aerodynamic loading properties on hood of high-speed railway tunnel☆

Yingxue Wang*, Wenqiang Ren, Jun He, Chang Ye, Qiaolei Chang

MOE Key Laboratory of Transportation Tunnel Engineering, Southwest Jiaotong University, Chengdu 610031, China

Received 23 October 2015; accepted 19 November 2015
Available online 18 December 2015

KEYWORDS
High-speed train;
Tunnel;
Hood;
Aerodynamic loading

Summary When high-speed train passing through tunnel, aerodynamic effect will be created, which may arise micro-pressure wave at tunnel exit and affect the surrounding environment around tunnel. Setting hood at tunnel entrance is effective and economical method. Using numeral simulation method, two kinds of hood mechanics character under deadweight and aerodynamic load were analysed. The stress concentration field on the hood and the magnitude of the stress caused by aerodynamic loading was defined. By comparing the aerodynamic loading method of pseudo-static and dynamic real-time, the necessity for doing real-time dynamic analysis is shown. The recommended kind of hood also was point out.
© 2016 Published by Elsevier GmbH. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

Introduction

When high-speed train passes through tunnel, a series of aerodynamic problems will be created. The effect of aerodynamic load on tunnel hood is one of these problems. The process of high-speed train entering the tunnel can be described as a piston movement in a pipe. When the high-speed train entering limited tunnel space from a three-dimensional semi-infinite space, compression wave and expansion wave will be induced and transmit in tunnel from one side to the other side at sound speed. Under the long-term tension and compression stress, tunnel structure is prone to fatigue damage. In order to relieve micro-pressure wave, the hood structure has a plurality of openings, thus reducing the structure's strength. On the other hand, the hood structure has more negative stress state than tunnel trunk because its structure is mostly open cut tunnel.

So, research of aerodynamic loading properties on hood structure is the key to tunnel structure safety analysis.

This paper will analyse the aerodynamic properties of several kinds of hood structures, evaluate the weak points and determine the recommended hood structure's form.

To this problem, some scholars have conducted some research about the peak of the tunnel's aerodynamic pressure and tunnel structural safety.

☆ This article is part of a special issue entitle ''Proceedings of the 1st Czech–China Scientific Conference''.

* Corresponding authors.
E-mail addresses: wangyingxue@swjtu.edu.cn (Y. Wang), 1026978930@qq.com (W. Ren).

http://dx.doi.org/10.1016/j.pisc.2015.12.004
2213-0209/© 2016 Published by Elsevier GmbH. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

Doctor Zhao Jing and Feng Zhipeng (Zhao, 2010; Feng et al., 2010), using numerical method, simulated the flow field of a single high-speed train passing and two high-speed trains meeting in tunnel. They analysed the variation characteristics of pressure wave in tunnel and the stress state on tunnel structure and carriages' window when high-speed trains meeting in tunnel.

Dr. Ma Weibin (Ma et al., 2012), from China Academy of Railway Sciences, discussed the research progress of high-speed railway tunnel aerodynamic effect, analysed the pressure fluctuation on subsidiary facilities when single train running or rendezvousing in tunnel, which can provide some reference for these facilities design.

Professor Ma Yundong (Ma et al., 2011), Dr. Fan Bin (Fan, 2010), based on meso-mechanics theory, the mechanical properties of tunnel lining vault's concrete under high-speed train passing through, was simulated. The concrete's stress state at different time was obtained, which could provide an important reference for the analysis of tunnel durability on consideration of aerodynamic load.

From the above research and analysis, it can be seen that the influence of aerodynamic loading on tunnel structure has attracted many scholars' attention, but pointing

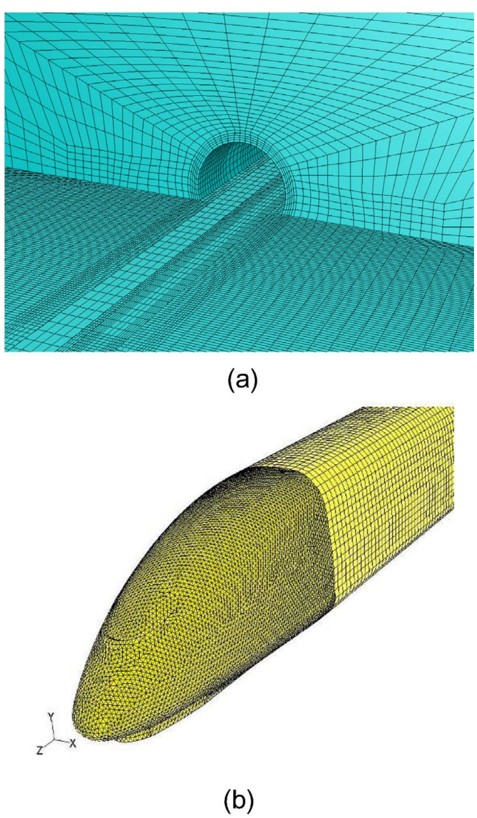


Figure 1 Mesh of the tunnel and train in simulation model.

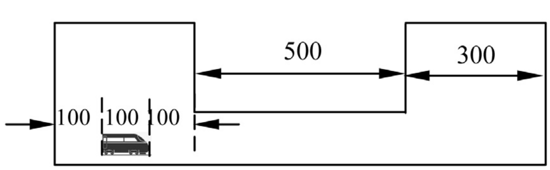


Figure 2 Dimension of numeral simulation model (unit: m).

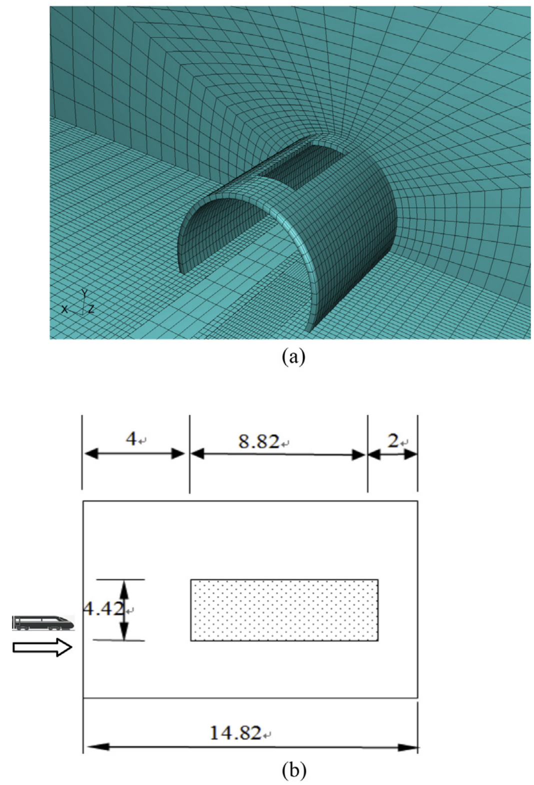


Figure 3 Single-top opening hood mesh and dimension (unit: m).

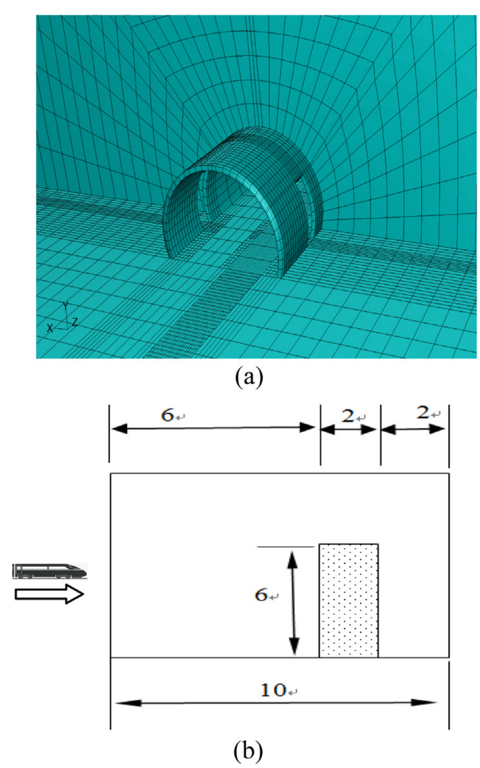


Figure 4 Single-side-strip opening hood mesh and dimension (unit: m).

to the character of high-speed railway tunnel, seldom research has been done on the aerodynamic loading properties on tunnel's structural opening, especially the hood structure.

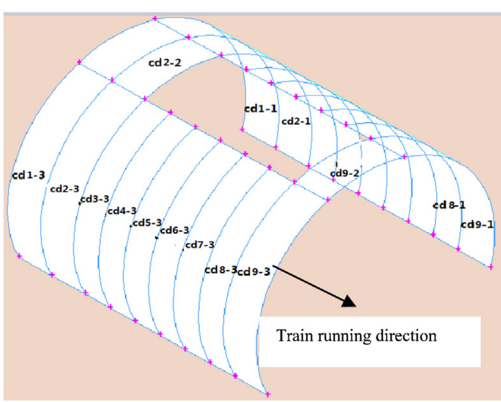
Governing equation

In this paper there are two parts of content: fluid dynamic field research and structure dynamic mechanics research. The structure dynamic mechanics research is only relevant to elastic analysis. So only the fluid dynamic theory will be introduced.

During the course of a high-speed train passing through a tunnel, the boundary conditions are changed with time. The dynamic meshing needs to be applied in the simulation model.

The integral form of the conservation equation for a general scalar, ϕ, on an arbitrary control volume, V, with moving boundaries is written as (Fluent Inc., 2004—09):

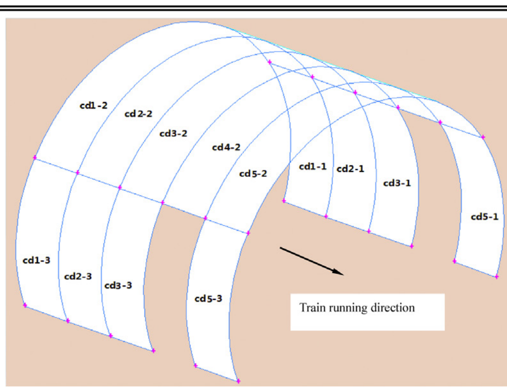
$$\frac{d}{dt}\int_V \rho\phi dV + \int_{\partial V} \rho\phi(\boldsymbol{u}-\boldsymbol{u}_g)\cdot d\boldsymbol{A} = \int_{\partial V} \Gamma\nabla\phi\cdot d\boldsymbol{A} + \int_V S_\phi dV, \tag{1}$$



(a)

TABLE I
HOOD MECHANICS PARAMETER

bulk density γ (KN/m^3)	Elastic modulus E (GPa)	Poisson's ratio μ
26.3	31.5	0.2



(b)

Figure 5 Hood surface partition graphics.

where ρ is the fluid density; $\boldsymbol{u}$ is the flow velocity vector; $\boldsymbol{u}_g$ is the grid velocity of the moving mesh; Γ is the diffusion coefficient; S_ϕ is the source term of ϕ; ∂V is used to represent the boundary of the control volume V.

Using a first-order backward difference formula, the time derivative term in (1) is written as

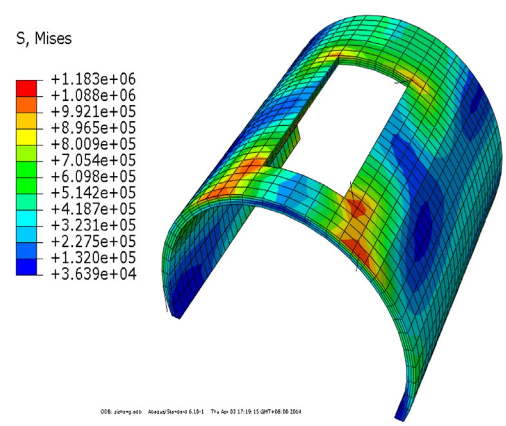
$$\frac{d}{dt}\int_V \rho\phi dV = \frac{(\rho\phi V)^{n+1} - (\rho\phi V)^n}{\Delta t}, \tag{2}$$

where n and $n+1$ denote the respective quantity at the current and next time level. The $(n+1)$th time level volume V^{n+1} is computed from

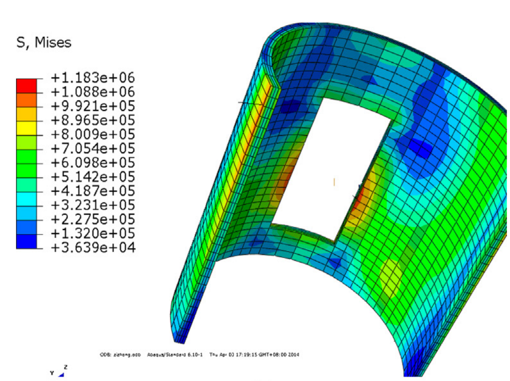
$$V^{n+1} = V^n + \frac{dV}{dt}\Delta t,$$

where dV/dt is the derivative of the control volume with respect to time. In order to satisfy the grid conservation law, dV/dt is computed from

$$\frac{dV}{dt} = \int_{\partial V} \boldsymbol{u}_g\cdot d\boldsymbol{A} = \sum_j^{n_f} \boldsymbol{u}_{g,j}\cdot \boldsymbol{A}_j, \tag{3}$$



(a)



(b)

Figure 6 Mises stress contour on single-top opening hood under deadweight (unit: Pa).

Table 1 Hood mechanics parameter.

Bulk density γ (kN/m^3)	Elastic modulus E (GPa)	Poisson's ratio μ
26.3	31.5	0.2

where n_f is the number of faces on the control volume and $\boldsymbol{A}_j$ is the j face area vector. The dot product $\boldsymbol{u}_{g,j} \cdot \boldsymbol{A}_j$ on each control volume face is calculated by

$$\boldsymbol{u}_{g,j} \cdot \boldsymbol{A}_j = \frac{\delta V_j}{\Delta t}, \tag{4}$$

where δV_j is the volume swept out by the control volume face j over the time step Δt.

Here, the large eddy simulation model (LES) is chosen. Pressure-far-field boundary conditions are adopted to simulate a free-stream condition. The transmission medium is assumed to be ideal gas.

Calculation parameter

For relief the induced micro-compression wave at tunnel exit, hood will be set at tunnel entrance. The hood usually has one or two openings on top or side. For abbreviation the content, only single opening hood will be analysed.

In the simulation model, the cross section area of tunnel is 100 m^2, and the type of train model is CRH3, the train cross section area is 11.624 m^2. The Speed of train is 350 km/h. The Length of tunnel is 500 m. The mesh of tunnel and train are shown in Fig. 1, and the total dimension of numeral simulation model is shown in Fig. 2.

For comparison the effect of different opening hood structure under aerodynamic loading, two kinds of hood, single-top opening hood and side-strip opening hood are chosen for analysis. The dimension of hood structures is shown in Figs. 3 and 4.

For monitoring the aerodynamic pressure on wall of the hood, hood surface was divided into different partitions. When train passes through tunnel, the pressure on each region was recorded separately. The different partitions of the hood are shown in Fig. 5. In fact, the hood has couple sides: inside and outside surface. Since mainly the internal side bears the aerodynamic load, so only the pressure on inside surface was monitored and recorded. The depth of hood structure is 0.5 m, and the other mechanics parameter was shown in Table 1.

Calculation results

Hood stress condition analysis under deadweight

Firstly, the stress condition of the tunnel under deadweight was analysed. In this condition, the von Mises stress contour on each hood is shown in Figs. 6 and 7.

From the Mises stress contour on hood under deadweight, it can be drawn out that:

- Maximum Mises stress on single strip-side opening hood is a little bigger than that on the single-top opening hood.
- The stress focus fields is almost same, all are near to the hood opening district.

Aerodynamic loading influence analysis

Two methods are used for applying aerodynamic load.

First method, peak pressure which got from simulation of training passing trough tunnel, as static load, is applied to each surface of the hood.

Second, using dynamic analysis method, the pressure-time curve of each monitoring surface is set back to the surface to calculate the hood stress condition.

Pressure curves at each monitoring surface for single-top opening hood are shown in Fig. 8. The pressure curves at each monitoring surface for single-strip-side opening hood is almost same, so it will not be given repeatedly.

The first calculation method—static analysis

Peak pressure on each monitoring surface is applied to single-top opening hood structure. Then the von Mises stress calculation result of structure is shown in Fig. 9.

Accordingly, Peak pressure on each monitoring surface is applied to single-side-strip opening hood structure. Then the von Mises stress calculation result of structure is shown in Fig. 10.

From the Mises stress contour graphics, It can be seen that:

- Under aerodynamic loading, von Mises stress on hood structure is asymmetry.

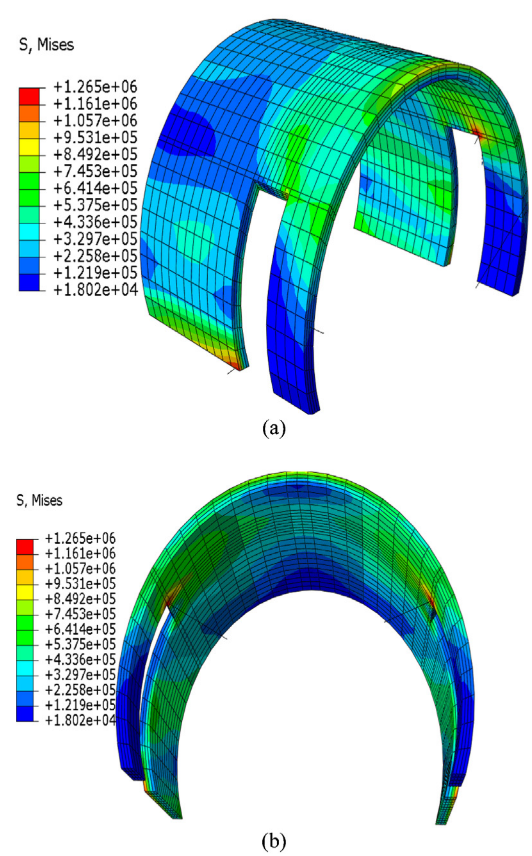


Figure 7 Mises stress contour on single-side-strip opening hood under deadweight (unit: Pa).

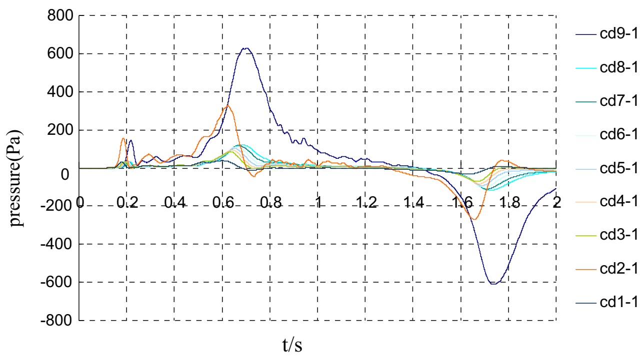
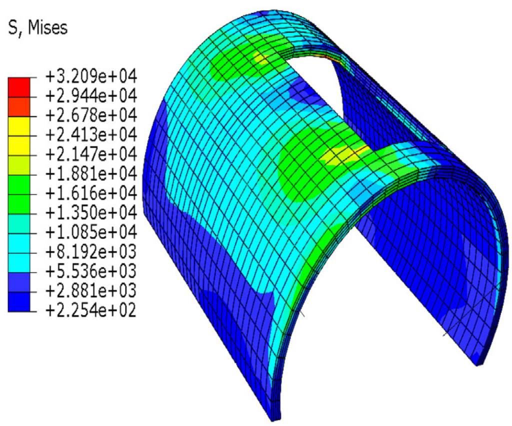
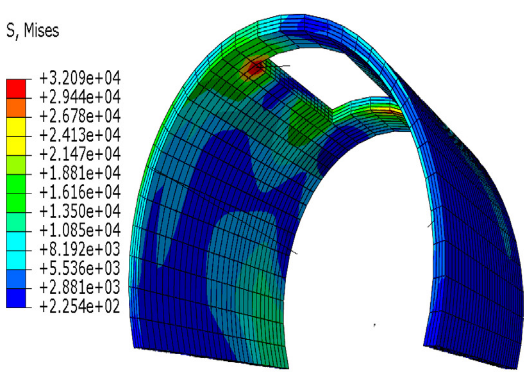


Figure 8 Single-top opening hood surface pressure monitoring curve.



(a)top view



(b) bottom view

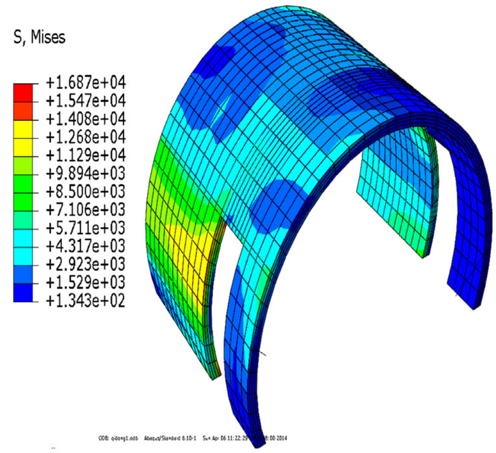
Figure 9 Mises stress contour on single-top opening hood under aerodynamic load (static analysis, unit: Pa).

- For the different opening hood, the maximum von Mises stress has much difference.

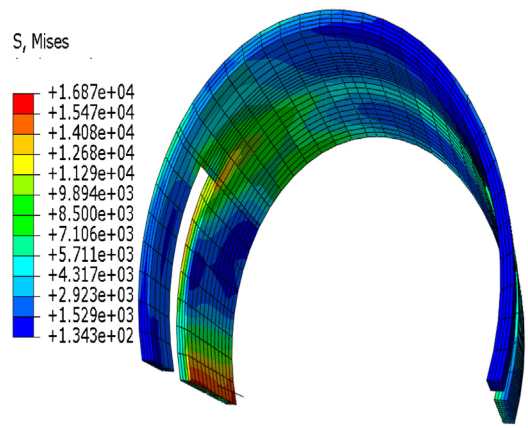
Maximum von Mises stress on single-top opening hood is 32.09 kPa, and the maximum von Mises stress on single-side-strip opening hood is only 16.87 kPa.

- The stress focus field is different.

The stress focus field for single-top opening hood is located at the top open of the structure, and the field for single-side-strip opening hood is mainly located at left



(a)top view



(b) bottom view

Figure 10 Mises stress contour on single-side-strip opening hood under aerodynamic load (static analysis, unit: Pa).

bottom of the hood structure. It shows that these regions are more likely to be affected by aerodynamic loading.

The second calculation method—dynamic analysis

For reducing the paper extension, only single-top opening hood is chosen for doing dynamic analysis. That is the pressure on each monitoring surface was set on the hood structure and done dynamic implicit analysis.

The process of train passing through tunnel hood is almost 2 s, accordingly the dynamic calculation is also 2 s.

The Mises stress contour on hood structure at 0.5 s and 1.5 s is shown in Fig. 11. By monitoring the von Mises stress on stress focus point, the dynamic von Mises stress curve is shown in Fig. 12.

From the Mises stress contour graphics and Mises stress-time variation curve on stress focus point of hood structure, it can be seen that:

- No matter static analysis or dynamic analysis, the stress condition is almost same.
- The von Mises stress focus field is also almost same, but the dynamic analysis result is rather bigger than static analysis result. The dynamic result of maximum von Mises stress is 60.75 kPa, which is almost double of the static analysis result.

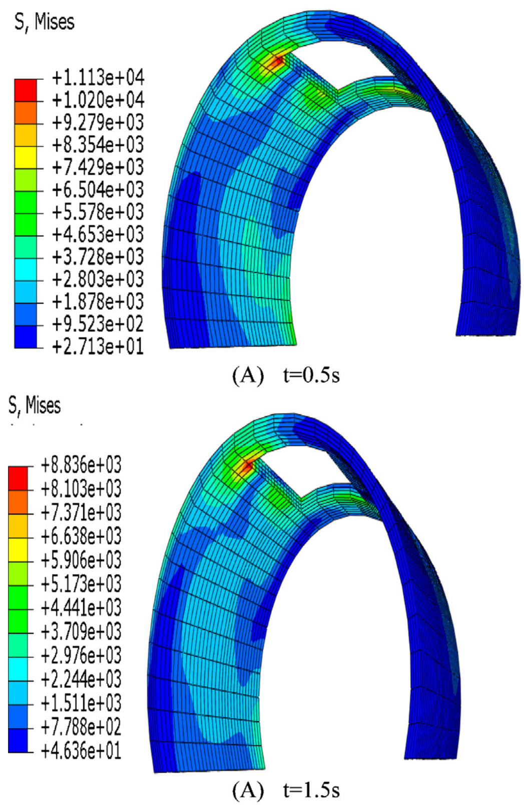


Figure 11 The Mises stress contour on hood structure (unit: Pa).

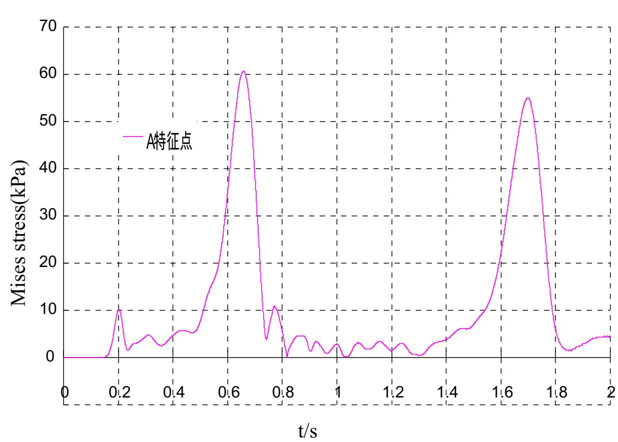


Figure 12 The Mises stress—time variation curve on stress focus point of hood structure.

- Comparing with the analysis result under deadweight, maximum von Mises stress induced by aerodynamic load is almost 5% of the stress induced by deadweight.

Conclusion

In this paper, using numerical method, the tunnel stress condition under aerodynamic load and deadweight was analysed, the following conclusions can be drawn out:

- Stress concentration field is mainly at the corner of the hood structure.
- The magnitude of the stress caused by aerodynamic loading is almost 5% of the stress induced by deadweight.
- By comparing the stress condition on hood structure under pseudo-static aerodynamic loading and dynamic real-time loading, the structural stress under dynamic real-time loading is obviously higher than that under pseudo-static aerodynamic loading, and doing real-time dynamic analysis is the necessity.
- Since the stress focus field is mainly at the corner of the hooding opening, in this case, the side side-strip opening hood is relatively safer to the top opening hood, and changing the rectangle corner to smooth curve is a wise choice to solve stress concentration.

Conflict of interest

The authors declare that there is no conflict of interest.

Acknowledgments

This paper is supported by the National High Technology Research and Development Program (''863''Program) of China (grant No. 2011AA11A103-3-3-2) and National Natural Science Foundation of China (Grant No. U1134208).

References

Fan, B., (Master Degree Thesis) 2010. Research on aerodynamic effect of high-speed railway tunnel and its impact on the durability of lining structure. Dalian Jiaotong University.

Feng, Z., Zhang, J., Zhang, W., 2010. Comparison and analysis of the aerodynamic performance of high-speed trains passing by each other inside tunnel and on open track. Rolling Stock 48, 1—6.

Fluent Inc., 2004—09. Fluent User's Guide, Lebanon, USA.

Ma, W., Zhang, Q., Liu, Y., 2012. Study evolvement of high-speed railway tunnel aerodynamic effect in China. J. Traffic Transp. Eng. 12, 29—36.

Ma, Y., Li, B., Fan, B., 2011. Mesomechanics numerical simulation of high-speed railway tunnel under the action of aerodynamic effect. J. Dalian Jiaotong Univ. 12, 16—19.

Zhao, J., (Doctoral Dissertation) 2010. A study on aerodynamic influence of high-speed trains passing tunnels. Southwest Jiaotong University.